Collisional Excitation of H$_2$O by H$_2$ Molecules

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ABSTRACT

Using an accurate theoretical rigid-rotor interaction potential for H_2O-H_2 and accurate coupled channel molecular scattering calculations, rates have been obtained for excitation of para- and ortho-H_2O out of the lowest, $j = 0$, 1, and 2, rotational levels owing to collisions with para- and ortho-H_2 at kinetic temperatures from 20 K to 140 K. Excitation by para-H_2 is not too different from excitation by He atoms, with most rates being within a factor of 1–3 larger, but excitation by ortho-H_2 is significantly different, with some rates an order of magnitude larger than rates for excitation by He atoms.

1. Introduction

Based on cosmic abundances and models of chemistry, water is expected to be an important constituent of the interstellar gas. Theoretical studies (Neufeld & Melnick 1987; Neufeld & Kaufman 1993; Neufeld, Lepp, & Melnick 1995) suggest water to be the major coolant of dense molecular cloud cores, although space-based observations are still needed to confirm the molecular abundances predicted in these studies; the water cooling rates also depend strongly on assumed collisional excitation rates. Ground based observations of water microwave and far infrared transitions are hampered by obscuration and confusion from telluric water. Observations of the fundamental $1_{0,1}-1_{1,0}$ transition in ortho-H_2O are one of the prime objectives of the Submillimeter Wave Astronomy Satellite (SWAS) project (Melnick et al. 1991; Goldsmith et al. 1991). However, rather spectacular maser emission is readily observed from the ground for several water transitions in star-forming regions and in the envelopes of some evolved stars (Neufeld & Melnick 1991; Melnick et al. 1993); these transitions are among higher-lying rotational levels which are not populated in the atmosphere.

Understanding thermal balance and interpretation of observed water emission both require a knowledge of collisional excitation rates responsible for line formation. In particular, the maser transitions are believed to be collisionally pumped, and excitation rates will be required to interpret the SWAS oberations in terms of kinetic temperatures, number densities, and fractional abundances. To date such studies have relied on rates of excitation of H_2O by collisions with He atoms. These rates have been obtained in a series of increasingly more accurate calculations and are now believed to be reliably known (Green, Maluendes, & McLean 1993). However, H_2 molecules are more abundant than He atoms in the interstellar gas by a factor of 4–5 so excitation by H_2 is the process of most interest. Because of the additional angular dependence of the interaction potential and because of

the additional H_2 rotational levels which must be included in coupled channel scattering calculations, theoretical studies of H_2 are much more difficult. It has been argued that rates of excitation by H_2, especially by cold para-H_2, are similar to those from excitation by He but computational expense has precluded tests of this hypothesis. Rapid advances in computational power in the last few years have finally made it possible to contemplate calculations for excitation by H_2 similar in accuracy to those which have been done for excitation by He.

Phillips et al. (1994) calculated the intermolecular potential between H_2O and H_2 at over 700 geometries using accurate quantum molecular structure methods and fitted the resulting points to a 48-term angular expansion which can be used to obtain a global representation. Phillips, Maluendes, & Green (1995) used this interaction potential in preliminary molecular scattering calculations. The close coupling method, which becomes exact on increasing the number of rotational levels included in the expansion basis set, was used to determine the size of calculations necessary to obtain converged cross sections at collision energies of a few hundred K. Converged values were then used to test the accuracy of the coupled states approximate method which is significantly cheaper. This study concluded that H_2O-H_2 cross sections, especially for collisions by ortho-H_2, may not be adequately represented by H_2O-He cross sections. However, it also demonstrated the feasibility of obtaining H_2O-H_2 cross sections, at least among the lower rotational levels and at enough energies to obtain thermally averaged rate constants for temperatures to a few hundred K, with currently available computational resources. The present work presents results of such calculations for the four combinations of para- and ortho-H_2O excited by para- and ortho-H_2. Rates have been obtained for excitation of H_2O out of its $j = 0$, 1, and 2 rotational levels and into the lowest ten levels for each symmetry species at temperatures from 20-140 K.

The next section provides details of the computational methods and the following

section presents results and compares with He excitation rates. The final section gives a brief discussion.

2. Details of Calculation

The H_2O-H_2 interaction potential was described in Phillips et al. (1994) and the molecular scattering formalism was described in Phillips, Maluendes, & Green (1995) which should be consulted for details. Rotational energies and wavefunctions for H_2O were the same as those described by Green, Maluendes, & McLean (1993) in their study of excitation of H_2O by He atoms. The rotational energy of H_2 was calculated from the rigid rotor formula using a rotation constant of 60.853 cm^{-1}. Close coupling and coupled states calculations were done with the MOLSCAT[1] computer code using the hybrid modified log derivative-Airy propagator of Alexander and Manolopoulos (1987) to solve the coupled equations. In general, numerical tolerances were chosen to obtain cross sections accurate to about 1%.

Phillips, Maluendes, & Green (1995) found that the $j = 2$ level was necessary in para-H_2 calculations to obtain cross sections converged to better than 10% even when this level was energetically inaccessible, and the present calculations generally included this level; however, at the highest collision energies a few of the deeply closed H_2O levels were paired only with $H_2(j = 0)$. Since the $j = 3$ level was found to be unnecessary for better than 10% accuracy in ortho-H_2 calculations, these included only the $j = 1$ level. Enough closed H_2O levels were included in each calculation to obtain cross sections which are believed, based

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[1] The MOLSCAT code was written by J.M. Hutson and S. Green and is distributed by Collaborative Computational Project No. 6 of the Engineering and Physical Sciences Research Council, UK. The program and documentation may be obtained over the World Wide Web at URL http://molscat.giss.nasa.gov/MOLSCAT/.

on the studies presented previously, to be converged to better than 5% for the transitions reported here. In general, this required including H_2O levels corresponding to at least one j value beyond the highest open j value.

Because nonreactive thermal collision do not interconvert the ortho- and para-forms of either species, calculations were done separately for the four combinations. The accurate close coupling method was used at lower energies — to 275 cm^{-1} for para-H_2O-para-H_2, to 420 cm^{-1} for para-H_2O-ortho-H_2, to 250 cm^{-1} for ortho-H_2O-para-H_2, and to 450 cm^{-1} for ortho-H_2O-ortho-H_2. These are total (collisional kinetic plus internal rotor) energies so that energies quoted for ortho-H_2 include H_2 rotational energy of about 120 cm^{-1}. Coupled states approximate calculations were used for higher energies, to about 750 cm^{-1} in each case. The coupled states method was found by Phillips, Maluendes, & Green (1995) to track the close coupling values reasonably well, with an accuracy of typically 10–20% at collision energies of a few hundred cm^{-1}, apparently improving, as expected, at higher energies. However, especially for excitation by ortho-H_2, coupled states occasionally gave errors on the order of 30–50% and comparisons made in the present work found similar behavior. Fortunately, cross sections at the higher energies where coupled states was used contribute only a small fraction to the thermal averages reported here. Calculations were done for 40-50 total energies for each symmetry combination to obtain averages over thermal distributions of collision energies for temperatures from 20-140 K; energies within a few cm^{-1} of excitation thresholds for each transition of interest were included in order to obtain accurate thermal averages at the lowest temperatures. The molecular scattering calculations required approximately 100–200 hours of computer time on a small workstation for each of the four symmetry cases.

3. Results

The molecular scattering calculations produce state-to-state cross sections, $\sigma(j\alpha, j_2 \rightarrow j'\alpha', j_2')$, where j is the H_2O rotational angular momentum quantum number, α specifies the other H_2O quantum numbers (e.g., K_{-1}, K_1), and j_2 specifies the H_2 rotational quantum number. Averaging cross sections over a thermal distribution of collision energies gives state-to-state rate constants, $R(j\alpha, j_2 \rightarrow j'\alpha', j_2')$. In general, astrophysical models require effective H_2O excitation rate constants which have also been averaged over a thermal distribution of H_2 initial rotational levels, j_2, and summed over all possible final H_2 levels, j_2',

$$\tilde{R}(j\alpha \rightarrow j'\alpha') = \sum_{j_2 j_2'} \rho(j_2) R(j\alpha, j_2 \rightarrow j'\alpha', j_2') \,, \tag{1}$$

where the fractional population in the H_2 rotational levels is given by

$$\rho(j_2) = (2j_2 + 1)g_{j_2} e^{(-E_{j_2}/kT)} / \sum_{j_2} (2j_2 + 1)g_{j_2} e^{(-E_{j_2}/kT)} \,. \tag{2}$$

The nuclear spin statistics degeneracy factor is $g_{j_2} = 1$ for para-H_2 (even j_2) and $g_{j_2} = 3$ for ortho-H_2 (odd j_2), k is Boltzmann's constant, and T is the temperature. This, of course, assumes that the H_2 molecules have a thermal distribution which is not always the case in astrophysical sources. In particular, the ortho/para ratio may not reflect the thermal temperature (e.g., Hoban, et al. 1991; Takayanagi, Sakimoto, & Onda 1987). It is therefore convenient to define an effective H_2O excitation rate which depends on the initial rotational level of the H_2 molecule, $\hat{R}_{j_2}(j\alpha \rightarrow j'\alpha')$ by summing over only the final H_2 rotational levels,

$$\hat{R}_{j_2}(j\alpha \rightarrow j'\alpha') = \sum_{j_2'} R(j\alpha, j_2 \rightarrow j'\alpha', j_2') \,. \tag{3}$$

It should be noted that the $R(j\alpha, j_2 \rightarrow j'\alpha', j_2')$ and $\tilde{R}(j\alpha \rightarrow j'\alpha')$ satisfy the usual detailed balance relations between forward and reverse rates, but that the $\hat{R}_{j_2}(j\alpha \rightarrow j'\alpha')$ do not, since they do not involve a complete thermal average. It is the $\hat{R}_{j_2}$ which are reported in the present study.

At the temperatures considered here only the lowest rotational level in each of the nuclear spin modifications of H_2 has significant population as can be readily determined from Eq (2). For ortho-H_2 at 140 K more than 99% of the population is in $j = 1$. For para-H_2 at 140 K, 90% is in $j = 0$; and at 100 K, over 97%.

Calculated rates for para-H_2O are given in Tables 1 and 2 for excitation by $H_2(j = 0)$ and $H_2(j = 1)$, respectively. Rates are reported for para-H_2O initially in the lowest five rotational levels, which correspond to the $j = 0$, 1, and 2 levels (all of the levels below 200 K); and for excitation to the lowest ten levels (all those below 450 K). The complete set of rates among the lowest ten levels is not reported since it is believed that somewhat larger rotational basis sets would be required to obtain values between the higher levels which are converged to better than 5-10%, the accuracy expected for those which are reported. These calculations also determined some of the rates for excitation of para-H_2O by $H_2(j = 2)$; those which are thought to be determined to the same accuracy are reported in Table 3. Rates out of the lowest five ortho-H_2O rotational levels ($j=1$ and 2, plus the lowest $j=3$ level since it lies very close in energy) are given in Tables 4 and 5 for excitation by $H_2(j = 0)$ and $H_2(j = 1)$, respectively, again into the lowest ten rotational levels. All the rate constants reported here are available in formats which can be read by computer.[2]

Since He excitation rates have been used in earlier work as surrogates for the H_2 rates it is of some interest to compare the present results with the He rates (Green, Maluendes, & McLean 1993). This is done in Table 6 for excitation of para-H_2O by $H_2(j = 0)$ and $H_2(j = 1)$ and similarly for ortho-H_2O in Table 7. For perspective, it has been thought that $H_2(j = 0)$ rates should generally be about 50% larger than He rates owing to the smaller

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[2]Rates may be obtained from S.G. (agxsg@giss.nasa.gov), or by anonymous ftp to molscat.giss.nasa.gov in directory pub/astrophys, or via the World Wide Web at URL http://molscat.giss.nasa.gov/rates/.

collisional reduced mass and the fact that the H_2 is somewhat larger than He. For $H_2(j = 1)$ excitation the situation was less clear but it was generally believed that *dipole allowed* H_2O transitions would be enhanced by a factor of 2–3 owing to the long-range dipole-quadrupole interaction which is effective in this case. The arguments leading to these conclusions are also based on the assumption that the short-range interaction for H_2, averaged over its orientations, is similar to that for He (see, e.g., Green 1977; Green 1986; Green 1991).

It is clear from Tables 6 and 7 that this is overly simplistic. In fact, the $H_2(j = 0)$ rates are generally within a factor of 1–3 of the He rates. The $H_2(j = 1)$ rates show more variation but some rates are enhanced by an order of magnitude or more. For excitation out of the lowest para-H_2O level, the most dramatic enhancements are for those cases where the cross section is identically zero for a spherical perturber in the coupled states approximation, for example, $0_{0,0} \rightarrow 2_{1,1}$, $0_{0,0} \rightarrow 3_{2,2}$, and $0_{0,0} \rightarrow 4_{1,3}$. In the full close coupling method these rates are not identically zero, but are found to be quite small. The inclusion of the $H_2(j = 2)$ levels, however, removes the spherical symmetry and greatly increases these rates. From Table 3 it should be clear that the difference between "para-H_2" and "ortho-H_2" is really a distinction between $H_2(j = 0)$ and H_2 in higher rotational levels; excitation rates for $H_2(j = 2)$ are, in general, comparable in magnitude to those for $H_2(j = 1)$. In fact, at lower temperatures excitation out of the ground state to the higher levels is enhanced over the $H_2(j = 0)$ rates due to collisions in which the H_2 is simultaneously deexcited from $j = 2$ to $j = 0$. At higher temperatures the rates for excitation by $H_2(j = 1)$ and $H_2(j = 2)$ are generally similar, but this comparison is limited by the the current paucity of results for the latter. The enhancement of rates by ortho-H_2 does not appear to correlate with line strengths (Chandra, Varshalovich, & Kegel 1984) as has been assumed. It is clear that, as noted by Phillips et al. (1994), the short-range interactions with H_2 and with He are less similar than previously hypothesized, and this precludes any simple scaling between excitation rates. Thus, while "cold para-H_2" does, to some extent, mimick a spherical He

atom, this phenomenon is really limited to quite low temperatures and the scaling factor is larger than expected; excitation rates differ in a complex way as soon as higher H_2 rotational levels, of either nuclear spin symmetry, are involved.

Finally, these calculations also give rates for excitation of $H_2(j = 0)$ to $H_2(j = 2)$ in collisions with H_2O. These are listed in Table 8 as a function of initial H_2O level, summed over final H_2O levels; these calculations were not designed to obtain this quantity, and only those values which appear to be adequately converged are included. Rotationally excited H_2O molecules are seen to be more effective in exciting H_2. Examination of the detailed state-to-state rates gives the expected reason: rates are enhanced when the H_2O molecule can be simultaneously deexcited.

4. Discussion

We consider here the accuracy of the calculated rate constants. Numerical errors in solving the coupled equations are only a percent or two. The rigid rotor basis sets are believed to give cross sections converged to better than 5%. The coupled states approximation, used at higher collision energies, may introduce errors of more than 25% in some cross sections but these make small contributions to thermal averages at the temperatures considered here. At very low temperatures care must be used to adequately resolve resonance structure in $\sigma(E)$ in order to obtain accurate thermal averages. In fact, little structure was observed here at low energies and it is not clear whether it was missed owing to the relatively coarse energy grids used (spacings of 3–5 cm^{-1}) or whether resonances in this system are weak owing to the widely spaced energy levels in both H_2 and H_2O. Judging from convergence of the thermal averages on including additional energies, however, they are believed to be accurate to better than 10%. Considering all this, rate constants presented here are believed accurate to better than 20% *for the assumed*

interaction potential.

It is somewhat more difficult to judge the errors owing to inaccuracy of the interaction potential. Considering the theoretical methods used by Phillips et al. (1994) in comparison with those used in successively more accurate studies of H_2O-He, it seems likely that errors from the interaction potential here for total excitation rates out of a given level are on the order of 20–30% although individual rate constants, which depend strongly on details of the anisotropy in the interaction, may be significantly less certain. A major uncertainty in the present work is the adequacy of the global fit to the over 700 points calculated for various H_2O-H_2 geometries; although a great deal of effort was spent on an accurate fit, there is little basis for judging it. As with H_2O-He some check can be obtained by comparing predicted collision induced spectral linewidths with experimental data (Liebe & Dillon 1969; Kasuga, Kuze, & Shimizu 1978; Goyette & DeLucia 1990; Dutta et al. 1993), but this requires extending calculations to the higher temperatures for which data are available; we plan to do such calculations.

A major conclusion of this work is that rates for excitation by H_2 are probably not adequately represented by (scaled) rates for excitation by He. The values presented here should therefore be very useful for revising models of thermal balance in dense molecular clouds and for analyzing observations of the $1_{0,1}$–$1_{1,0}$ transition planned for the SWAS project. Modeling of the extremely interesting maser transitions, however, will require extension of the present calculations to higher energies. Although straightforward, this will require a large amount of computer time even by current standards.

Table 1.   Excitation rates of p-H_2O in collisions with $H_2(j = 0)$[a]

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$0_{0,0}$	$1_{1,1}$	3.17×10^{-12}	1.21×10^{-11}	1.98×10^{-11}	2.66×10^{-11}	3.31×10^{-11}	3.94×10^{-11}	4.56×10^{-11}
$0_{0,0}$	$2_{0,2}$	4.72×10^{-13}	6.02×10^{-12}	1.38×10^{-11}	2.08×10^{-11}	2.65×10^{-11}	3.12×10^{-11}	3.50×10^{-11}
$0_{0,0}$	$2_{1,1}$	8.42×10^{-16}	3.05×10^{-14}	8.99×10^{-14}	1.46×10^{-13}	1.91×10^{-13}	2.26×10^{-13}	2.53×10^{-13}
$0_{0,0}$	$2_{2,0}$	2.99×10^{-16}	4.55×10^{-14}	2.62×10^{-13}	6.55×10^{-13}	1.17×10^{-12}	1.76×10^{-12}	2.41×10^{-12}
$0_{0,0}$	$3_{1,3}$	6.97×10^{-16}	1.15×10^{-13}	6.43×10^{-13}	1.56×10^{-12}	2.71×10^{-12}	3.98×10^{-12}	5.33×10^{-12}
$0_{0,0}$	$3_{2,2}$	4.78×10^{-21}	8.04×10^{-18}	9.19×10^{-17}	3.13×10^{-16}	6.75×10^{-16}	1.18×10^{-15}	1.89×10^{-15}
$0_{0,0}$	$4_{0,4}$	1.54×10^{-19}	5.24×10^{-16}	8.72×10^{-15}	3.82×10^{-14}	9.83×10^{-14}	1.93×10^{-13}	3.25×10^{-13}
$0_{0,0}$	$4_{1,3}$	9.74×10^{-34}	1.06×10^{-23}	2.52×10^{-20}	1.29×10^{-18}	1.41×10^{-17}	7.12×10^{-17}	2.31×10^{-16}
$0_{0,0}$	$3_{3,1}$	2.71×10^{-22}	7.73×10^{-18}	2.43×10^{-16}	1.38×10^{-15}	3.90×10^{-15}	7.81×10^{-15}	1.28×10^{-14}
$1_{1,1}$	$0_{0,0}$	1.53×10^{-11}	1.53×10^{-11}	1.61×10^{-11}	1.73×10^{-11}	1.88×10^{-11}	2.05×10^{-11}	2.24×10^{-11}
$1_{1,1}$	$2_{0,2}$	1.55×10^{-12}	5.34×10^{-12}	8.38×10^{-12}	1.09×10^{-11}	1.33×10^{-11}	1.55×10^{-11}	1.76×10^{-11}
$1_{1,1}$	$2_{1,1}$	1.33×10^{-12}	1.14×10^{-11}	2.28×10^{-11}	3.20×10^{-11}	3.91×10^{-11}	4.46×10^{-11}	4.89×10^{-11}
$1_{1,1}$	$2_{2,0}$	2.43×10^{-14}	8.43×10^{-13}	2.82×10^{-12}	5.29×10^{-12}	7.88×10^{-12}	1.05×10^{-11}	1.30×10^{-11}
$1_{1,1}$	$3_{1,3}$	7.01×10^{-15}	3.17×10^{-13}	1.14×10^{-12}	2.19×10^{-12}	3.27×10^{-12}	4.33×10^{-12}	5.33×10^{-12}
$1_{1,1}$	$3_{2,2}$	2.12×10^{-17}	9.90×10^{-15}	7.98×10^{-14}	2.33×10^{-13}	4.52×10^{-13}	7.13×10^{-13}	9.99×10^{-13}
$1_{1,1}$	$4_{0,4}$	1.28×10^{-17}	1.07×10^{-14}	1.05×10^{-13}	3.39×10^{-13}	6.98×10^{-13}	1.15×10^{-12}	1.66×10^{-12}
$1_{1,1}$	$4_{1,3}$	2.07×10^{-21}	1.26×10^{-17}	2.61×10^{-16}	1.29×10^{-15}	3.53×10^{-15}	7.18×10^{-15}	1.22×10^{-14}
$1_{1,1}$	$3_{3,1}$	1.30×10^{-20}	1.08×10^{-16}	2.36×10^{-15}	1.18×10^{-14}	3.28×10^{-14}	6.76×10^{-14}	1.18×10^{-13}
$2_{0,2}$	$0_{0,0}$	1.46×10^{-11}	1.50×10^{-11}	1.49×10^{-11}	1.47×10^{-11}	1.46×10^{-11}	1.46×10^{-11}	1.45×10^{-11}
$2_{0,2}$	$1_{1,1}$	9.95×10^{-12}	1.05×10^{-11}	1.11×10^{-11}	1.19×10^{-11}	1.28×10^{-11}	1.38×10^{-11}	1.49×10^{-11}
$2_{0,2}$	$2_{1,1}$	1.81×10^{-12}	5.68×10^{-12}	9.06×10^{-12}	1.21×10^{-11}	1.50×10^{-11}	1.79×10^{-11}	2.07×10^{-11}
$2_{0,2}$	$2_{2,0}$	4.03×10^{-14}	4.27×10^{-13}	9.16×10^{-13}	1.32×10^{-12}	1.64×10^{-12}	1.89×10^{-12}	2.11×10^{-12}
$2_{0,2}$	$3_{1,3}$	2.41×10^{-13}	3.08×10^{-12}	7.17×10^{-12}	1.10×10^{-11}	1.45×10^{-11}	1.78×10^{-11}	2.08×10^{-11}
$2_{0,2}$	$3_{2,2}$	2.25×10^{-16}	3.35×10^{-14}	1.84×10^{-13}	4.49×10^{-13}	7.90×10^{-13}	1.18×10^{-12}	1.61×10^{-12}
$2_{0,2}$	$4_{0,4}$	7.72×10^{-17}	2.35×10^{-14}	1.70×10^{-13}	4.72×10^{-13}	8.84×10^{-13}	1.36×10^{-12}	1.87×10^{-12}
$2_{0,2}$	$4_{1,3}$	2.52×10^{-19}	4.44×10^{-16}	5.55×10^{-15}	2.03×10^{-14}	4.54×10^{-14}	7.96×10^{-14}	1.22×10^{-13}
$2_{0,2}$	$3_{3,1}$	5.97×10^{-20}	1.45×10^{-16}	2.06×10^{-15}	8.21×10^{-15}	1.95×10^{-14}	3.58×10^{-14}	5.65×10^{-14}

Table 1—Continued

initial	final	Temperature, K						
		20.0	40.0	60.0	80.0	100.0	120.0	140.0
$2_{1,1}$	$0_{0,0}$	1.59×10^{-13}	1.88×10^{-13}	1.78×10^{-13}	1.72×10^{-13}	1.75×10^{-13}	1.87×10^{-13}	2.08×10^{-13}
$2_{1,1}$	$1_{1,1}$	5.20×10^{-11}	5.51×10^{-11}	5.51×10^{-11}	5.46×10^{-11}	5.41×10^{-11}	5.37×10^{-11}	5.34×10^{-11}
$2_{1,1}$	$2_{0,2}$	1.10×10^{-11}	1.40×10^{-11}	1.65×10^{-11}	1.90×10^{-11}	2.16×10^{-11}	2.43×10^{-11}	2.69×10^{-11}
$2_{1,1}$	$2_{2,0}$	7.99×10^{-13}	3.56×10^{-12}	6.09×10^{-12}	8.26×10^{-12}	1.02×10^{-11}	1.20×10^{-11}	1.38×10^{-11}
$2_{1,1}$	$3_{1,3}$	2.20×10^{-13}	1.12×10^{-12}	1.90×10^{-12}	2.47×10^{-12}	2.91×10^{-12}	3.27×10^{-12}	3.58×10^{-12}
$2_{1,1}$	$3_{2,2}$	8.64×10^{-15}	4.78×10^{-13}	1.85×10^{-12}	3.72×10^{-12}	5.78×10^{-12}	7.91×10^{-12}	1.01×10^{-11}
$2_{1,1}$	$4_{0,4}$	4.79×10^{-16}	4.85×10^{-14}	2.35×10^{-13}	5.34×10^{-13}	8.97×10^{-13}	1.30×10^{-12}	1.71×10^{-12}
$2_{1,1}$	$4_{1,3}$	8.84×10^{-18}	6.55×10^{-15}	6.38×10^{-14}	2.09×10^{-13}	4.42×10^{-13}	7.46×10^{-13}	1.10×10^{-12}
$2_{1,1}$	$3_{3,1}$	7.01×10^{-19}	6.82×10^{-16}	7.26×10^{-15}	2.52×10^{-14}	5.62×10^{-14}	9.98×10^{-14}	1.55×10^{-13}
$2_{2,0}$	$0_{0,0}$	1.08×10^{-12}	1.22×10^{-12}	1.37×10^{-12}	1.54×10^{-12}	1.70×10^{-12}	1.88×10^{-12}	2.08×10^{-12}
$2_{2,0}$	$1_{1,1}$	1.82×10^{-11}	1.79×10^{-11}	1.82×10^{-11}	1.89×10^{-11}	1.98×10^{-11}	2.08×10^{-11}	2.19×10^{-11}
$2_{2,0}$	$2_{0,2}$	4.68×10^{-12}	4.60×10^{-12}	4.47×10^{-12}	4.34×10^{-12}	4.25×10^{-12}	4.21×10^{-12}	4.19×10^{-12}
$2_{2,0}$	$2_{1,1}$	1.53×10^{-11}	1.55×10^{-11}	1.63×10^{-11}	1.73×10^{-11}	1.84×10^{-11}	1.97×10^{-11}	2.11×10^{-11}
$2_{2,0}$	$3_{1,3}$	2.97×10^{-12}	3.63×10^{-12}	3.87×10^{-12}	4.19×10^{-12}	4.58×10^{-12}	5.02×10^{-12}	5.49×10^{-12}
$2_{2,0}$	$3_{2,2}$	1.69×10^{-13}	2.31×10^{-12}	5.54×10^{-12}	8.62×10^{-12}	1.13×10^{-11}	1.36×10^{-11}	1.55×10^{-11}
$2_{2,0}$	$4_{0,4}$	1.14×10^{-15}	2.88×10^{-14}	8.76×10^{-14}	1.61×10^{-13}	2.46×10^{-13}	3.45×10^{-13}	4.60×10^{-13}
$2_{2,0}$	$4_{1,3}$	2.03×10^{-16}	3.09×10^{-14}	1.68×10^{-13}	4.01×10^{-13}	6.90×10^{-13}	1.01×10^{-12}	1.34×10^{-12}
$2_{2,0}$	$3_{3,1}$	5.69×10^{-16}	1.34×10^{-13}	8.66×10^{-13}	2.27×10^{-12}	4.16×10^{-12}	6.34×10^{-12}	8.70×10^{-12}

[a]Rates in units of cm^3 sec^{-1}

Table 2. Excitation rates of p-H_2O in collisions with $H_2(j = 1)$[a]

initial	final				Temperature, K			
		20.0	40.0	60.0	80.0	100.0	120.0	140.0
$0_{0,0}$	$1_{1,1}$	2.19×10^{-11}	9.47×10^{-11}	1.60×10^{-10}	2.10×10^{-10}	2.48×10^{-10}	2.78×10^{-10}	3.03×10^{-10}
$0_{0,0}$	$2_{0,2}$	8.31×10^{-13}	1.10×10^{-11}	2.67×10^{-11}	4.18×10^{-11}	5.50×10^{-11}	6.63×10^{-11}	7.59×10^{-11}
$0_{0,0}$	$2_{1,1}$	3.36×10^{-14}	1.10×10^{-12}	3.44×10^{-12}	6.08×10^{-12}	8.60×10^{-12}	1.09×10^{-11}	1.30×10^{-11}
$0_{0,0}$	$2_{2,0}$	1.90×10^{-15}	2.88×10^{-13}	1.63×10^{-12}	3.99×10^{-12}	6.90×10^{-12}	1.00×10^{-11}	1.33×10^{-11}
$0_{0,0}$	$3_{1,3}$	6.30×10^{-16}	1.11×10^{-13}	6.46×10^{-13}	1.61×10^{-12}	2.84×10^{-12}	4.24×10^{-12}	5.74×10^{-12}
$0_{0,0}$	$3_{2,2}$	7.48×10^{-19}	1.02×10^{-15}	1.15×10^{-14}	4.00×10^{-14}	8.72×10^{-14}	1.50×10^{-13}	2.26×10^{-13}
$0_{0,0}$	$4_{0,4}$	9.90×10^{-19}	3.02×10^{-15}	4.37×10^{-14}	1.68×10^{-13}	3.85×10^{-13}	6.79×10^{-13}	1.03×10^{-12}
$0_{0,0}$	$4_{1,3}$	5.69×10^{-21}	1.09×10^{-16}	2.96×10^{-15}	1.59×10^{-14}	4.51×10^{-14}	9.28×10^{-14}	1.58×10^{-13}
$0_{0,0}$	$3_{3,1}$	3.13×10^{-21}	9.20×10^{-17}	3.07×10^{-15}	1.89×10^{-14}	5.87×10^{-14}	1.29×10^{-13}	2.34×10^{-13}
$1_{1,1}$	$0_{0,0}$	1.06×10^{-10}	1.20×10^{-10}	1.30×10^{-10}	1.36×10^{-10}	1.41×10^{-10}	1.45×10^{-10}	1.48×10^{-10}
$1_{1,1}$	$2_{0,2}$	2.51×10^{-11}	8.23×10^{-11}	1.17×10^{-10}	1.37×10^{-10}	1.48×10^{-10}	1.54×10^{-10}	1.59×10^{-10}
$1_{1,1}$	$2_{1,1}$	2.27×10^{-12}	2.08×10^{-11}	4.39×10^{-11}	6.40×10^{-11}	8.04×10^{-11}	9.38×10^{-11}	1.05×10^{-10}
$1_{1,1}$	$2_{2,0}$	5.73×10^{-14}	2.25×10^{-12}	7.95×10^{-12}	1.51×10^{-11}	2.22×10^{-11}	2.88×10^{-11}	3.48×10^{-11}
$1_{1,1}$	$3_{1,3}$	1.99×10^{-14}	9.36×10^{-13}	3.45×10^{-12}	6.64×10^{-12}	9.88×10^{-12}	1.29×10^{-11}	1.57×10^{-11}
$1_{1,1}$	$3_{2,2}$	4.93×10^{-17}	2.13×10^{-14}	1.67×10^{-13}	4.81×10^{-13}	9.36×10^{-13}	1.49×10^{-12}	2.12×10^{-12}
$1_{1,1}$	$4_{0,4}$	1.95×10^{-17}	1.56×10^{-14}	1.50×10^{-13}	4.82×10^{-13}	9.93×10^{-13}	1.64×10^{-12}	2.38×10^{-12}
$1_{1,1}$	$4_{1,3}$	1.00×10^{-19}	5.13×10^{-16}	9.00×10^{-15}	3.87×10^{-14}	9.47×10^{-14}	1.75×10^{-13}	2.75×10^{-13}
$1_{1,1}$	$3_{3,1}$	1.29×10^{-19}	9.89×10^{-16}	2.06×10^{-14}	9.87×10^{-14}	2.61×10^{-13}	5.14×10^{-13}	8.52×10^{-13}
$2_{0,2}$	$0_{0,0}$	2.58×10^{-11}	2.75×10^{-11}	2.86×10^{-11}	2.95×10^{-11}	3.02×10^{-11}	3.07×10^{-11}	3.12×10^{-11}
$2_{0,2}$	$1_{1,1}$	1.61×10^{-10}	1.62×10^{-10}	1.55×10^{-10}	1.48×10^{-10}	1.42×10^{-10}	1.38×10^{-10}	1.34×10^{-10}
$2_{0,2}$	$2_{1,1}$	3.49×10^{-11}	9.32×10^{-11}	1.29×10^{-10}	1.52×10^{-10}	1.69×10^{-10}	1.82×10^{-10}	1.92×10^{-10}
$2_{0,2}$	$2_{2,0}$	2.35×10^{-13}	2.61×10^{-12}	5.91×10^{-12}	8.97×10^{-12}	1.16×10^{-11}	1.38×10^{-11}	1.58×10^{-11}
$2_{0,2}$	$3_{1,3}$	5.52×10^{-13}	8.56×10^{-12}	2.18×10^{-11}	3.46×10^{-11}	4.53×10^{-11}	5.40×10^{-11}	6.13×10^{-11}
$2_{0,2}$	$3_{2,2}$	1.45×10^{-15}	2.05×10^{-13}	1.08×10^{-12}	2.54×10^{-12}	4.30×10^{-12}	6.22×10^{-12}	8.21×10^{-12}
$2_{0,2}$	$4_{0,4}$	3.09×10^{-16}	7.80×10^{-14}	4.95×10^{-13}	1.26×10^{-12}	2.25×10^{-12}	3.36×10^{-12}	4.54×10^{-12}
$2_{0,2}$	$4_{1,3}$	1.51×10^{-18}	2.50×10^{-15}	3.03×10^{-14}	1.10×10^{-13}	2.44×10^{-13}	4.26×10^{-13}	6.47×10^{-13}
$2_{0,2}$	$3_{3,1}$	4.04×10^{-19}	9.29×10^{-16}	1.29×10^{-14}	5.01×10^{-14}	1.17×10^{-13}	2.11×10^{-13}	3.29×10^{-13}

Table 2—Continued

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$2_{1,1}$	$0_{0,0}$	6.35×10^{-12}	6.74×10^{-12}	6.74×10^{-12}	6.74×10^{-12}	6.77×10^{-12}	6.82×10^{-12}	6.90×10^{-12}
$2_{1,1}$	$1_{1,1}$	8.88×10^{-11}	1.01×10^{-10}	1.06×10^{-10}	1.09×10^{-10}	1.11×10^{-10}	1.13×10^{-10}	1.14×10^{-10}
$2_{1,1}$	$2_{0,2}$	2.12×10^{-10}	2.30×10^{-10}	2.35×10^{-10}	2.39×10^{-10}	2.42×10^{-10}	2.45×10^{-10}	2.49×10^{-10}
$2_{1,1}$	$2_{2,0}$	7.45×10^{-12}	3.54×10^{-11}	5.92×10^{-11}	7.58×10^{-11}	8.74×10^{-11}	9.59×10^{-11}	1.02×10^{-10}
$2_{1,1}$	$3_{1,3}$	2.35×10^{-12}	1.31×10^{-11}	2.25×10^{-11}	2.91×10^{-11}	3.36×10^{-11}	3.68×10^{-11}	3.91×10^{-11}
$2_{1,1}$	$3_{2,2}$	1.45×10^{-14}	8.41×10^{-13}	3.28×10^{-12}	6.51×10^{-12}	9.90×10^{-12}	1.32×10^{-11}	1.64×10^{-11}
$2_{1,1}$	$4_{0,4}$	1.49×10^{-15}	1.49×10^{-13}	6.92×10^{-13}	1.50×10^{-12}	2.43×10^{-12}	3.39×10^{-12}	4.35×10^{-12}
$2_{1,1}$	$4_{1,3}$	2.32×10^{-17}	1.56×10^{-14}	1.42×10^{-13}	4.48×10^{-13}	9.20×10^{-13}	1.52×10^{-12}	2.23×10^{-12}
$2_{1,1}$	$3_{3,1}$	8.05×10^{-18}	7.62×10^{-15}	7.93×10^{-14}	2.68×10^{-13}	5.75×10^{-13}	9.80×10^{-13}	1.46×10^{-12}
$2_{2,0}$	$0_{0,0}$	6.86×10^{-12}	7.73×10^{-12}	8.57×10^{-12}	9.24×10^{-12}	9.80×10^{-12}	1.03×10^{-11}	1.08×10^{-11}
$2_{2,0}$	$1_{1,1}$	4.28×10^{-11}	4.76×10^{-11}	5.13×10^{-11}	5.38×10^{-11}	5.55×10^{-11}	5.67×10^{-11}	5.78×10^{-11}
$2_{2,0}$	$2_{0,2}$	2.73×10^{-11}	2.82×10^{-11}	2.88×10^{-11}	2.94×10^{-11}	3.00×10^{-11}	3.06×10^{-11}	3.11×10^{-11}
$2_{2,0}$	$2_{1,1}$	1.42×10^{-10}	1.55×10^{-10}	1.58×10^{-10}	1.58×10^{-10}	1.58×10^{-10}	1.57×10^{-10}	1.56×10^{-10}
$2_{2,0}$	$3_{1,3}$	3.11×10^{-11}	3.74×10^{-11}	3.86×10^{-11}	3.89×10^{-11}	3.92×10^{-11}	3.94×10^{-11}	3.95×10^{-11}
$2_{2,0}$	$3_{2,2}$	4.68×10^{-13}	6.31×10^{-12}	1.48×10^{-11}	2.24×10^{-11}	2.87×10^{-11}	3.41×10^{-11}	3.88×10^{-11}
$2_{2,0}$	$4_{0,4}$	1.77×10^{-14}	4.24×10^{-13}	1.18×10^{-12}	1.95×10^{-12}	2.67×10^{-12}	3.33×10^{-12}	3.95×10^{-12}
$2_{2,0}$	$4_{1,3}$	6.29×10^{-16}	8.88×10^{-14}	4.62×10^{-13}	1.07×10^{-12}	1.79×10^{-12}	2.56×10^{-12}	3.34×10^{-12}
$2_{2,0}$	$3_{3,1}$	1.09×10^{-15}	2.38×10^{-13}	1.48×10^{-12}	3.79×10^{-12}	6.80×10^{-12}	1.02×10^{-11}	1.38×10^{-11}

[a]Rates in units of $cm^3\ sec^{-1}$

Table 3. Excitation rates of p-H_2O in collisions with $H_2(j=2)$[a]

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$0_{0,0}$	$1_{1,1}$	1.65×10^{-11}	6.25×10^{-11}	1.03×10^{-10}	1.36×10^{-10}	1.65×10^{-10}	1.91×10^{-10}	2.14×10^{-10}
$0_{0,0}$	$2_{0,2}$	2.47×10^{-12}	1.06×10^{-11}	2.31×10^{-11}	3.55×10^{-11}	4.70×10^{-11}	5.72×10^{-11}	6.63×10^{-11}
$0_{0,0}$	$2_{1,1}$	1.35×10^{-12}	1.98×10^{-12}	3.59×10^{-12}	5.74×10^{-12}	8.08×10^{-12}	1.05×10^{-11}	1.28×10^{-11}
$0_{0,0}$	$2_{2,0}$	1.21×10^{-12}	1.29×10^{-12}	1.81×10^{-12}	2.84×10^{-12}	4.26×10^{-12}	5.95×10^{-12}	7.83×10^{-12}
$0_{0,0}$	$3_{1,3}$	7.45×10^{-13}	7.41×10^{-13}	1.13×10^{-12}	1.90×10^{-12}	2.88×10^{-12}	3.94×10^{-12}	5.04×10^{-12}

[a]Rates in units of cm^3 sec^{-1}

Table 4.   Excitation rates of o-H_2O in collisions with $H_2(j = 0)$[a]

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$1_{0,1}$	$1_{1,0}$	3.06×10^{-12}	8.20×10^{-12}	1.21×10^{-11}	1.55×10^{-11}	1.87×10^{-11}	2.18×10^{-11}	2.49×10^{-11}
$1_{0,1}$	$2_{1,2}$	6.10×10^{-13}	4.87×10^{-12}	9.87×10^{-12}	1.44×10^{-11}	1.85×10^{-11}	2.24×10^{-11}	2.61×10^{-11}
$1_{0,1}$	$2_{2,1}$	2.42×10^{-15}	1.42×10^{-13}	5.56×10^{-13}	1.11×10^{-12}	1.70×10^{-12}	2.29×10^{-12}	2.86×10^{-12}
$1_{0,1}$	$3_{0,3}$	5.88×10^{-15}	3.51×10^{-13}	1.37×10^{-12}	2.74×10^{-12}	4.18×10^{-12}	5.59×10^{-12}	6.93×10^{-12}
$1_{0,1}$	$3_{1,2}$	2.26×10^{-17}	4.76×10^{-15}	2.88×10^{-14}	7.26×10^{-14}	1.30×10^{-13}	1.96×10^{-13}	2.70×10^{-13}
$1_{0,1}$	$3_{2,1}$	1.74×10^{-18}	1.66×10^{-15}	1.81×10^{-14}	6.46×10^{-14}	1.46×10^{-13}	2.64×10^{-13}	4.12×10^{-13}
$1_{0,1}$	$4_{1,4}$	5.98×10^{-18}	8.27×10^{-15}	9.52×10^{-14}	3.32×10^{-13}	7.17×10^{-13}	1.22×10^{-12}	1.81×10^{-12}
$1_{0,1}$	$3_{3,0}$	8.57×10^{-22}	1.09×10^{-17}	2.66×10^{-16}	1.35×10^{-15}	3.61×10^{-15}	7.03×10^{-15}	1.14×10^{-14}
$1_{0,1}$	$4_{2,3}$	8.05×10^{-22}	1.86×10^{-17}	5.74×10^{-16}	3.40×10^{-15}	1.04×10^{-14}	2.29×10^{-14}	4.14×10^{-14}
$1_{1,0}$	$1_{0,1}$	1.17×10^{-11}	1.60×10^{-11}	1.89×10^{-11}	2.16×10^{-11}	2.44×10^{-11}	2.72×10^{-11}	3.03×10^{-11}
$1_{1,0}$	$2_{1,2}$	1.94×10^{-12}	7.38×10^{-12}	1.10×10^{-11}	1.33×10^{-11}	1.48×10^{-11}	1.59×10^{-11}	1.67×10^{-11}
$1_{1,0}$	$2_{2,1}$	4.44×10^{-14}	1.25×10^{-12}	3.89×10^{-12}	7.05×10^{-12}	1.03×10^{-11}	1.35×10^{-11}	1.67×10^{-11}
$1_{1,0}$	$3_{0,3}$	9.90×10^{-15}	2.89×10^{-13}	9.04×10^{-13}	1.65×10^{-12}	2.43×10^{-12}	3.22×10^{-12}	4.02×10^{-12}
$1_{1,0}$	$3_{1,2}$	8.63×10^{-16}	9.96×10^{-14}	5.07×10^{-13}	1.18×10^{-12}	2.00×10^{-12}	2.89×10^{-12}	3.80×10^{-12}
$1_{1,0}$	$3_{2,1}$	2.56×10^{-18}	1.35×10^{-15}	1.21×10^{-14}	3.85×10^{-14}	8.04×10^{-14}	1.36×10^{-13}	2.01×10^{-13}
$1_{1,0}$	$4_{1,4}$	2.12×10^{-18}	1.68×10^{-15}	1.71×10^{-14}	5.85×10^{-14}	1.30×10^{-13}	2.35×10^{-13}	3.71×10^{-13}
$1_{1,0}$	$3_{3,0}$	2.45×10^{-20}	1.53×10^{-16}	3.02×10^{-15}	1.43×10^{-14}	3.87×10^{-14}	7.85×10^{-14}	1.35×10^{-13}
$1_{1,0}$	$4_{2,3}$	2.57×10^{-20}	3.09×10^{-16}	7.57×10^{-15}	3.94×10^{-14}	1.10×10^{-13}	2.22×10^{-13}	3.75×10^{-13}
$2_{1,2}$	$1_{0,1}$	2.02×10^{-11}	2.17×10^{-11}	2.25×10^{-11}	2.35×10^{-11}	2.47×10^{-11}	2.63×10^{-11}	2.78×10^{-11}
$2_{1,2}$	$1_{1,0}$	1.68×10^{-11}	1.68×10^{-11}	1.61×10^{-11}	1.56×10^{-11}	1.52×10^{-11}	1.49×10^{-11}	1.48×10^{-11}
$2_{1,2}$	$2_{2,1}$	1.64×10^{-13}	1.17×10^{-12}	2.38×10^{-12}	3.55×10^{-12}	4.71×10^{-12}	5.87×10^{-12}	7.03×10^{-12}
$2_{1,2}$	$3_{0,3}$	5.01×10^{-13}	3.74×10^{-12}	7.32×10^{-12}	1.05×10^{-11}	1.33×10^{-11}	1.59×10^{-11}	1.84×10^{-11}
$2_{1,2}$	$3_{1,2}$	3.12×10^{-14}	9.07×10^{-13}	2.81×10^{-12}	5.01×10^{-12}	7.13×10^{-12}	9.09×10^{-12}	1.09×10^{-11}
$2_{1,2}$	$3_{2,1}$	8.95×10^{-16}	1.08×10^{-13}	5.52×10^{-13}	1.29×10^{-12}	2.21×10^{-12}	3.22×10^{-12}	4.29×10^{-12}
$2_{1,2}$	$4_{1,4}$	1.42×10^{-16}	3.02×10^{-14}	1.90×10^{-13}	4.91×10^{-13}	8.86×10^{-13}	1.33×10^{-12}	1.81×10^{-12}
$2_{1,2}$	$3_{3,0}$	2.08×10^{-19}	3.52×10^{-16}	4.53×10^{-15}	1.73×10^{-14}	4.04×10^{-14}	7.42×10^{-14}	1.18×10^{-13}
$2_{1,2}$	$4_{2,3}$	1.20×10^{-19}	3.61×10^{-16}	5.40×10^{-15}	2.15×10^{-14}	5.01×10^{-14}	8.93×10^{-14}	1.36×10^{-13}

Table 4—Continued

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$2_{2,1}$	$1_{0,1}$	4.32×10^{-12}	4.64×10^{-12}	4.80×10^{-12}	4.95×10^{-12}	5.10×10^{-12}	5.28×10^{-12}	5.49×10^{-12}
$2_{2,1}$	$1_{1,0}$	2.08×10^{-11}	2.09×10^{-11}	2.15×10^{-11}	2.23×10^{-11}	2.35×10^{-11}	2.49×10^{-11}	2.63×10^{-11}
$2_{2,1}$	$2_{1,2}$	8.84×10^{-12}	8.63×10^{-12}	8.99×10^{-12}	9.64×10^{-12}	1.05×10^{-11}	1.14×10^{-11}	1.25×10^{-11}
$2_{2,1}$	$3_{0,3}$	2.76×10^{-12}	2.72×10^{-12}	2.55×10^{-12}	2.43×10^{-12}	2.36×10^{-12}	2.34×10^{-12}	2.34×10^{-12}
$2_{2,1}$	$3_{1,2}$	8.43×10^{-13}	3.10×10^{-12}	4.66×10^{-12}	5.76×10^{-12}	6.67×10^{-12}	7.50×10^{-12}	8.28×10^{-12}
$2_{2,1}$	$3_{2,1}$	1.06×10^{-13}	1.80×10^{-12}	4.72×10^{-12}	7.75×10^{-12}	1.06×10^{-11}	1.30×10^{-11}	1.52×10^{-11}
$2_{2,1}$	$4_{1,4}$	3.84×10^{-15}	8.61×10^{-14}	2.51×10^{-13}	4.48×10^{-13}	6.59×10^{-13}	8.82×10^{-13}	1.11×10^{-12}
$2_{2,1}$	$3_{3,0}$	5.77×10^{-16}	1.35×10^{-13}	8.63×10^{-13}	2.26×10^{-12}	4.12×10^{-12}	6.26×10^{-12}	8.59×10^{-12}
$2_{2,1}$	$4_{2,3}$	1.16×10^{-17}	5.32×10^{-15}	4.48×10^{-14}	1.37×10^{-13}	2.77×10^{-13}	4.54×10^{-13}	6.59×10^{-13}
$3_{0,3}$	$1_{0,1}$	8.56×10^{-12}	8.78×10^{-12}	8.86×10^{-12}	9.00×10^{-12}	9.19×10^{-12}	9.46×10^{-12}	9.77×10^{-12}
$3_{0,3}$	$1_{1,0}$	3.79×10^{-12}	3.70×10^{-12}	3.73×10^{-12}	3.87×10^{-12}	4.06×10^{-12}	4.33×10^{-12}	4.62×10^{-12}
$3_{0,3}$	$2_{1,2}$	2.21×10^{-11}	2.10×10^{-11}	2.06×10^{-11}	2.09×10^{-11}	2.16×10^{-11}	2.27×10^{-11}	2.38×10^{-11}
$3_{0,3}$	$2_{2,1}$	2.26×10^{-12}	2.08×10^{-12}	1.90×10^{-12}	1.79×10^{-12}	1.73×10^{-12}	1.71×10^{-12}	1.71×10^{-12}
$3_{0,3}$	$3_{1,2}$	1.02×10^{-12}	3.83×10^{-12}	6.24×10^{-12}	8.37×10^{-12}	1.04×10^{-11}	1.24×10^{-11}	1.44×10^{-11}
$3_{0,3}$	$3_{2,1}$	1.10×10^{-14}	1.70×10^{-13}	4.28×10^{-13}	6.86×10^{-13}	9.19×10^{-13}	1.12×10^{-12}	1.31×10^{-12}
$3_{0,3}$	$4_{1,4}$	6.94×10^{-14}	1.67×10^{-12}	4.90×10^{-12}	8.51×10^{-12}	1.20×10^{-11}	1.53×10^{-11}	1.85×10^{-11}
$3_{0,3}$	$3_{3,0}$	1.87×10^{-17}	3.80×10^{-15}	2.35×10^{-14}	6.07×10^{-14}	1.10×10^{-13}	1.68×10^{-13}	2.32×10^{-13}
$3_{0,3}$	$4_{2,3}$	1.89×10^{-17}	7.62×10^{-15}	5.99×10^{-14}	1.76×10^{-13}	3.50×10^{-13}	5.70×10^{-13}	8.26×10^{-13}

[a]Rates in units of cm^3 sec^{-1}

Table 5.   Excitation rates of o-H$_2$O in collisions with H$_2(j = 1)$[a]

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$1_{0,1}$	$1_{1,0}$	7.04×10^{-11}	1.47×10^{-10}	1.85×10^{-10}	2.07×10^{-10}	2.21×10^{-10}	2.31×10^{-10}	2.40×10^{-10}
$1_{0,1}$	$2_{1,2}$	2.94×10^{-12}	2.52×10^{-11}	5.28×10^{-11}	7.68×10^{-11}	9.59×10^{-11}	1.11×10^{-10}	1.23×10^{-10}
$1_{0,1}$	$2_{2,1}$	1.20×10^{-14}	7.14×10^{-13}	2.90×10^{-12}	5.96×10^{-12}	9.26×10^{-12}	1.25×10^{-11}	1.56×10^{-11}
$1_{0,1}$	$3_{0,3}$	1.16×10^{-14}	7.41×10^{-13}	3.09×10^{-12}	6.38×10^{-12}	9.91×10^{-12}	1.33×10^{-11}	1.66×10^{-11}
$1_{0,1}$	$3_{1,2}$	2.31×10^{-16}	5.41×10^{-14}	3.35×10^{-13}	8.46×10^{-13}	1.50×10^{-12}	2.21×10^{-12}	2.96×10^{-12}
$1_{0,1}$	$3_{2,1}$	1.11×10^{-17}	1.12×10^{-14}	1.16×10^{-13}	3.83×10^{-13}	7.99×10^{-13}	1.33×10^{-12}	1.95×10^{-12}
$1_{0,1}$	$4_{1,4}$	5.89×10^{-18}	8.34×10^{-15}	9.87×10^{-14}	3.55×10^{-13}	7.92×10^{-13}	1.38×10^{-12}	2.10×10^{-12}
$1_{0,1}$	$3_{3,0}$	1.58×10^{-20}	1.92×10^{-16}	4.69×10^{-15}	2.45×10^{-14}	6.91×10^{-14}	1.42×10^{-13}	2.44×10^{-13}
$1_{0,1}$	$4_{2,3}$	3.27×10^{-21}	6.87×10^{-17}	1.96×10^{-15}	1.09×10^{-14}	3.17×10^{-14}	6.64×10^{-14}	1.16×10^{-13}
$1_{1,0}$	$1_{0,1}$	2.68×10^{-10}	2.86×10^{-10}	2.89×10^{-10}	2.89×10^{-10}	2.88×10^{-10}	2.89×10^{-10}	2.91×10^{-10}
$1_{1,0}$	$2_{1,2}$	1.11×10^{-11}	4.31×10^{-11}	6.49×10^{-11}	7.80×10^{-11}	8.61×10^{-11}	9.14×10^{-11}	9.51×10^{-11}
$1_{1,0}$	$2_{2,1}$	1.16×10^{-13}	3.51×10^{-12}	1.14×10^{-11}	2.08×10^{-11}	3.00×10^{-11}	3.82×10^{-11}	4.55×10^{-11}
$1_{1,0}$	$3_{0,3}$	4.44×10^{-14}	1.27×10^{-12}	3.83×10^{-12}	6.64×10^{-12}	9.25×10^{-12}	1.16×10^{-11}	1.37×10^{-11}
$1_{1,0}$	$3_{1,2}$	1.80×10^{-15}	2.35×10^{-13}	1.24×10^{-12}	2.87×10^{-12}	4.76×10^{-12}	6.72×10^{-12}	8.66×10^{-12}
$1_{1,0}$	$3_{2,1}$	2.60×10^{-17}	1.30×10^{-14}	1.08×10^{-13}	3.20×10^{-13}	6.27×10^{-13}	9.97×10^{-13}	1.41×10^{-12}
$1_{1,0}$	$4_{1,4}$	1.70×10^{-17}	1.24×10^{-14}	1.15×10^{-13}	3.57×10^{-13}	7.21×10^{-13}	1.17×10^{-12}	1.68×10^{-12}
$1_{1,0}$	$3_{3,0}$	2.37×10^{-19}	1.47×10^{-15}	2.84×10^{-14}	1.30×10^{-13}	3.36×10^{-13}	6.50×10^{-13}	1.06×10^{-12}
$1_{1,0}$	$4_{2,3}$	3.64×10^{-20}	4.21×10^{-16}	1.01×10^{-14}	5.23×10^{-14}	1.46×10^{-13}	2.97×10^{-13}	5.04×10^{-13}
$2_{1,2}$	$1_{0,1}$	9.71×10^{-11}	1.12×10^{-10}	1.21×10^{-10}	1.25×10^{-10}	1.28×10^{-10}	1.30×10^{-10}	1.31×10^{-10}
$2_{1,2}$	$1_{1,0}$	9.67×10^{-11}	9.83×10^{-11}	9.50×10^{-11}	9.13×10^{-11}	8.81×10^{-11}	8.56×10^{-11}	8.35×10^{-11}
$2_{1,2}$	$2_{2,1}$	1.52×10^{-12}	1.21×10^{-11}	2.42×10^{-11}	3.41×10^{-11}	4.15×10^{-11}	4.71×10^{-11}	5.15×10^{-11}
$2_{1,2}$	$3_{0,3}$	1.91×10^{-12}	1.68×10^{-11}	3.51×10^{-11}	5.03×10^{-11}	6.19×10^{-11}	7.06×10^{-11}	7.74×10^{-11}
$2_{1,2}$	$3_{1,2}$	7.92×10^{-14}	2.54×10^{-12}	8.15×10^{-12}	1.46×10^{-11}	2.07×10^{-11}	2.61×10^{-11}	3.09×10^{-11}
$2_{1,2}$	$3_{2,1}$	2.11×10^{-15}	2.76×10^{-13}	1.43×10^{-12}	3.32×10^{-12}	5.55×10^{-12}	7.91×10^{-12}	1.03×10^{-11}
$2_{1,2}$	$4_{1,4}$	5.34×10^{-16}	1.06×10^{-13}	6.20×10^{-13}	1.51×10^{-12}	2.61×10^{-12}	3.80×10^{-12}	5.03×10^{-12}
$2_{1,2}$	$3_{3,0}$	1.77×10^{-18}	2.87×10^{-15}	3.52×10^{-14}	1.29×10^{-13}	2.91×10^{-13}	5.15×10^{-13}	7.88×10^{-13}
$2_{1,2}$	$4_{2,3}$	5.54×10^{-19}	1.44×10^{-15}	2.02×10^{-14}	7.78×10^{-14}	1.80×10^{-13}	3.24×10^{-13}	5.02×10^{-13}

Table 5—Continued

		Temperature, K						
initial	final	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$2_{2,1}$	$1_{0,1}$	2.15×10^{-11}	2.33×10^{-11}	2.50×10^{-11}	2.64×10^{-11}	2.75×10^{-11}	2.85×10^{-11}	2.94×10^{-11}
$2_{2,1}$	$1_{1,0}$	5.42×10^{-11}	5.89×10^{-11}	6.31×10^{-11}	6.61×10^{-11}	6.81×10^{-11}	6.96×10^{-11}	7.08×10^{-11}
$2_{2,1}$	$2_{1,2}$	8.19×10^{-11}	8.88×10^{-11}	9.16×10^{-11}	9.23×10^{-11}	9.21×10^{-11}	9.16×10^{-11}	9.10×10^{-11}
$2_{2,1}$	$3_{0,3}$	4.48×10^{-11}	4.64×10^{-11}	4.34×10^{-11}	4.04×10^{-11}	3.78×10^{-11}	3.59×10^{-11}	3.43×10^{-11}
$2_{2,1}$	$3_{1,2}$	3.95×10^{-12}	1.76×10^{-11}	2.82×10^{-11}	3.49×10^{-11}	3.92×10^{-11}	4.20×10^{-11}	4.40×10^{-11}
$2_{2,1}$	$3_{2,1}$	2.31×10^{-13}	4.39×10^{-12}	1.18×10^{-11}	1.92×10^{-11}	2.58×10^{-11}	3.17×10^{-11}	3.69×10^{-11}
$2_{2,1}$	$4_{1,4}$	1.60×10^{-14}	4.31×10^{-13}	1.28×10^{-12}	2.21×10^{-12}	3.08×10^{-12}	3.88×10^{-12}	4.61×10^{-12}
$2_{2,1}$	$3_{3,0}$	1.03×10^{-15}	2.30×10^{-13}	1.44×10^{-12}	3.69×10^{-12}	6.63×10^{-12}	9.93×10^{-12}	1.34×10^{-11}
$2_{2,1}$	$4_{2,3}$	5.24×10^{-17}	2.10×10^{-14}	1.63×10^{-13}	4.74×10^{-13}	9.26×10^{-13}	1.48×10^{-12}	2.10×10^{-12}
$3_{0,3}$	$1_{0,1}$	1.69×10^{-11}	1.85×10^{-11}	1.99×10^{-11}	2.09×10^{-11}	2.16×10^{-11}	2.22×10^{-11}	2.27×10^{-11}
$3_{0,3}$	$1_{1,0}$	1.70×10^{-11}	1.62×10^{-11}	1.58×10^{-11}	1.56×10^{-11}	1.54×10^{-11}	1.54×10^{-11}	1.55×10^{-11}
$3_{0,3}$	$2_{1,2}$	8.40×10^{-11}	9.42×10^{-11}	9.91×10^{-11}	1.01×10^{-10}	1.01×10^{-10}	1.00×10^{-10}	9.96×10^{-11}
$3_{0,3}$	$2_{2,1}$	3.66×10^{-11}	3.54×10^{-11}	3.24×10^{-11}	2.98×10^{-11}	2.78×10^{-11}	2.62×10^{-11}	2.50×10^{-11}
$3_{0,3}$	$3_{1,2}$	1.28×10^{-11}	5.25×10^{-11}	8.28×10^{-11}	1.03×10^{-10}	1.17×10^{-10}	1.27×10^{-10}	1.35×10^{-10}
$3_{0,3}$	$3_{2,1}$	1.02×10^{-13}	1.60×10^{-12}	4.08×10^{-12}	6.60×10^{-12}	8.90×10^{-12}	1.09×10^{-11}	1.27×10^{-11}
$3_{0,3}$	$4_{1,4}$	1.23×10^{-13}	3.19×10^{-12}	9.32×10^{-12}	1.58×10^{-11}	2.17×10^{-11}	2.70×10^{-11}	3.19×10^{-11}
$3_{0,3}$	$3_{3,0}$	9.21×10^{-17}	1.48×10^{-14}	7.82×10^{-14}	1.84×10^{-13}	3.15×10^{-13}	4.61×10^{-13}	6.16×10^{-13}
$3_{0,3}$	$4_{2,3}$	1.39×10^{-16}	5.06×10^{-14}	3.70×10^{-13}	1.03×10^{-12}	1.96×10^{-12}	3.07×10^{-12}	4.30×10^{-12}

[a] Rates in units of $cm^3 \ sec^{-1}$

Table 6.   Comparison of rates for p-H$_2$O excited by He, p-H$_2$, and o-H$_2$ at 120 K[a]

initial	final	He	p-H$_2$	o-H$_2$	p-H$_2$/He	o-H$_2$/He
$0_{0,0}$	$1_{1,1}$	3.43×10^{-11}	3.94×10^{-11}	2.78×10^{-10}	1.1	8.1
$0_{0,0}$	$2_{0,2}$	1.33×10^{-11}	3.12×10^{-11}	6.63×10^{-11}	2.3	5.0
$0_{0,0}$	$2_{1,1}$	2.27×10^{-14}	2.26×10^{-13}	1.09×10^{-11}	10.0	480.2
$0_{0,0}$	$2_{2,0}$	7.61×10^{-13}	1.76×10^{-12}	1.00×10^{-11}	2.3	13.1
$0_{0,0}$	$3_{1,3}$	3.98×10^{-12}	3.98×10^{-12}	4.24×10^{-12}	1.0	1.1
$0_{0,0}$	$3_{2,2}$	1.26×10^{-16}	1.18×10^{-15}	1.50×10^{-13}	9.4	1190.5
$0_{0,0}$	$4_{0,4}$	4.19×10^{-13}	1.93×10^{-13}	6.79×10^{-13}	0.5	1.6
$0_{0,0}$	$4_{1,3}$	2.59×10^{-16}	7.12×10^{-17}	9.28×10^{-14}	0.3	358.3
$0_{0,0}$	$3_{3,1}$	3.46×10^{-15}	7.81×10^{-15}	1.29×10^{-13}	2.3	37.3
$1_{1,1}$	$2_{0,2}$	1.51×10^{-11}	1.55×10^{-11}	1.54×10^{-10}	1.0	10.2
$1_{1,1}$	$2_{1,1}$	1.47×10^{-11}	4.46×10^{-11}	9.38×10^{-11}	3.0	6.4
$1_{1,1}$	$2_{2,0}$	5.65×10^{-12}	1.05×10^{-11}	2.88×10^{-11}	1.9	5.1
$1_{1,1}$	$3_{1,3}$	2.31×10^{-12}	4.33×10^{-12}	1.29×10^{-11}	1.9	5.6
$1_{1,1}$	$3_{2,2}$	4.45×10^{-13}	7.13×10^{-13}	1.49×10^{-12}	1.6	3.3
$1_{1,1}$	$4_{0,4}$	8.13×10^{-13}	1.15×10^{-12}	1.64×10^{-12}	1.4	2.0
$1_{1,1}$	$4_{1,3}$	8.97×10^{-15}	7.18×10^{-15}	1.75×10^{-13}	0.8	19.5
$1_{1,1}$	$3_{3,1}$	7.10×10^{-14}	6.76×10^{-14}	5.14×10^{-13}	1.0	7.2

Table 6—Continued

initial	final	He	p-H$_2$	o-H$_2$	p-H$_2$/He	o-H$_2$/He
$2_{0,2}$	$2_{1,1}$	1.53×10^{-11}	1.79×10^{-11}	1.82×10^{-10}	1.2	11.9
$2_{0,2}$	$2_{2,0}$	5.96×10^{-13}	1.89×10^{-12}	1.38×10^{-11}	3.2	23.2
$2_{0,2}$	$3_{1,3}$	1.12×10^{-11}	1.78×10^{-11}	5.40×10^{-11}	1.6	4.8
$2_{0,2}$	$3_{2,2}$	8.58×10^{-13}	1.18×10^{-12}	6.22×10^{-12}	1.4	7.2
$2_{0,2}$	$4_{0,4}$	4.15×10^{-13}	1.36×10^{-12}	3.36×10^{-12}	3.3	8.1
$2_{0,2}$	$4_{1,3}$	5.48×10^{-14}	7.96×10^{-14}	4.26×10^{-13}	1.5	7.8
$2_{0,2}$	$3_{3,1}$	1.42×10^{-14}	3.58×10^{-14}	2.11×10^{-13}	2.5	14.9
$2_{1,1}$	$2_{2,0}$	9.58×10^{-12}	1.20×10^{-11}	9.59×10^{-11}	1.3	10.0
$2_{1,1}$	$3_{1,3}$	2.51×10^{-12}	3.27×10^{-12}	3.68×10^{-11}	1.3	14.7
$2_{1,1}$	$3_{2,2}$	4.11×10^{-12}	7.91×10^{-12}	1.32×10^{-11}	1.9	3.2
$2_{1,1}$	$4_{0,4}$	1.45×10^{-12}	1.30×10^{-12}	3.39×10^{-12}	0.9	2.3
$2_{1,1}$	$4_{1,3}$	3.38×10^{-13}	7.46×10^{-13}	1.52×10^{-12}	2.2	4.5
$2_{1,1}$	$3_{3,1}$	1.45×10^{-13}	9.98×10^{-14}	9.80×10^{-13}	0.7	6.8
$2_{2,0}$	$3_{1,3}$	5.36×10^{-12}	5.02×10^{-12}	3.94×10^{-11}	0.9	7.4
$2_{2,0}$	$3_{2,2}$	4.99×10^{-12}	1.36×10^{-11}	3.41×10^{-11}	2.7	6.8
$2_{2,0}$	$4_{0,4}$	1.28×10^{-12}	3.45×10^{-13}	3.33×10^{-12}	0.3	2.6
$2_{2,0}$	$4_{1,3}$	8.45×10^{-13}	1.01×10^{-12}	2.56×10^{-12}	1.2	3.0
$2_{2,0}$	$3_{3,1}$	2.86×10^{-12}	6.34×10^{-12}	1.02×10^{-11}	2.2	3.6

[a]Rates in units of cm^3 sec^{-1}

Table 7. Comparison of rates for o-H_2O excited by He, p-H_2, and o-H_2 at 120 K[a]

initial	final	He	p-H_2	o-H_2	p-H_2/He	o-H_2/He
$1_{0,1}$	$1_{1,0}$	1.9×10^{-11}	2.2×10^{-11}	2.3×10^{-10}	1.1	12.2
$1_{0,1}$	$2_{1,2}$	1.9×10^{-11}	2.2×10^{-11}	1.1×10^{-10}	1.2	6.0
$1_{0,1}$	$2_{2,1}$	6.4×10^{-13}	2.3×10^{-12}	1.3×10^{-11}	3.6	19.5
$1_{0,1}$	$3_{0,3}$	2.2×10^{-12}	5.6×10^{-12}	1.3×10^{-11}	2.5	5.9
$1_{0,1}$	$3_{1,2}$	1.9×10^{-13}	2.0×10^{-13}	2.2×10^{-12}	1.0	11.6
$1_{0,1}$	$3_{2,1}$	3.4×10^{-13}	2.6×10^{-13}	1.3×10^{-12}	0.8	3.9
$1_{0,1}$	$4_{1,4}$	7.2×10^{-13}	1.2×10^{-12}	1.4×10^{-12}	1.7	1.9
$1_{0,1}$	$3_{3,0}$	2.8×10^{-15}	7.0×10^{-15}	1.4×10^{-13}	2.6	51.6
$1_{0,1}$	$4_{2,3}$	3.2×10^{-14}	2.3×10^{-14}	6.6×10^{-14}	0.7	2.1
$1_{1,0}$	$2_{1,2}$	8.6×10^{-12}	1.6×10^{-11}	9.1×10^{-11}	1.8	10.6
$1_{1,0}$	$2_{2,1}$	7.6×10^{-12}	1.4×10^{-11}	3.8×10^{-11}	1.8	5.0
$1_{1,0}$	$3_{0,3}$	4.8×10^{-12}	3.2×10^{-12}	1.2×10^{-11}	0.7	2.4
$1_{1,0}$	$3_{1,2}$	1.1×10^{-12}	2.9×10^{-12}	6.7×10^{-12}	2.6	6.0
$1_{1,0}$	$3_{2,1}$	1.1×10^{-13}	1.4×10^{-13}	1.0×10^{-12}	1.2	8.8
$1_{1,0}$	$4_{1,4}$	6.4×10^{-13}	2.4×10^{-13}	1.2×10^{-12}	0.4	1.8
$1_{1,0}$	$3_{3,0}$	9.2×10^{-14}	7.9×10^{-14}	6.5×10^{-13}	0.8	7.0
$1_{1,0}$	$4_{2,3}$	8.2×10^{-14}	2.2×10^{-13}	3.0×10^{-13}	2.7	3.6

Table 7—Continued

initial	final	He	p-H$_2$	o-H$_2$	p-H$_2$/He	o-H$_2$/He
$2_{1,2}$	$2_{2,1}$	6.8×10^{-12}	5.9×10^{-12}	4.7×10^{-11}	0.9	6.9
$2_{1,2}$	$3_{0,3}$	1.1×10^{-11}	1.6×10^{-11}	7.1×10^{-11}	1.4	6.4
$2_{1,2}$	$3_{1,2}$	3.0×10^{-12}	9.1×10^{-12}	2.6×10^{-11}	3.0	8.6
$2_{1,2}$	$3_{2,1}$	2.0×10^{-12}	3.2×10^{-12}	7.9×10^{-12}	1.6	4.0
$2_{1,2}$	$4_{1,4}$	4.0×10^{-13}	1.3×10^{-12}	3.8×10^{-12}	3.4	9.6
$2_{1,2}$	$3_{3,0}$	7.9×10^{-14}	7.4×10^{-14}	5.2×10^{-13}	0.9	6.5
$2_{1,2}$	$4_{2,3}$	3.2×10^{-14}	8.9×10^{-14}	3.2×10^{-13}	2.8	10.3
$2_{2,1}$	$3_{0,3}$	2.1×10^{-12}	2.3×10^{-12}	3.6×10^{-11}	1.1	17.2
$2_{2,1}$	$3_{1,2}$	5.4×10^{-12}	7.5×10^{-12}	4.2×10^{-11}	1.4	7.7
$2_{2,1}$	$3_{2,1}$	4.7×10^{-12}	1.3×10^{-11}	3.2×10^{-11}	2.8	6.7
$2_{2,1}$	$4_{1,4}$	1.7×10^{-12}	8.8×10^{-13}	3.9×10^{-12}	0.5	2.3
$2_{2,1}$	$3_{3,0}$	2.7×10^{-12}	6.3×10^{-12}	9.9×10^{-12}	2.3	3.7
$2_{2,1}$	$4_{2,3}$	1.3×10^{-13}	4.5×10^{-13}	1.5×10^{-12}	3.5	11.6
$3_{0,3}$	$3_{1,2}$	1.0×10^{-11}	1.2×10^{-11}	1.3×10^{-10}	1.2	12.7
$3_{0,3}$	$3_{2,1}$	3.7×10^{-13}	1.1×10^{-12}	1.1×10^{-11}	3.0	29.3
$3_{0,3}$	$4_{1,4}$	8.6×10^{-12}	1.5×10^{-11}	2.7×10^{-11}	1.8	3.1
$3_{0,3}$	$3_{3,0}$	1.3×10^{-13}	1.7×10^{-13}	4.6×10^{-13}	1.3	3.5
$3_{0,3}$	$4_{2,3}$	4.4×10^{-13}	5.7×10^{-13}	3.1×10^{-12}	1.3	7.0

[a]Rates in units of cm^3 sec^{-1}

Table 8. Excitation rates for H_2 $j = 0 \to 2$ in collisions with H_2O J_{K_{-1},K_1}.[a]

J_{K_{-1},K_1}	Temperature, K						
	20.0	40.0	60.0	80.0	100.0	120.0	140.0
$0_{0,0}$	3.9×10^{-24}	3.3×10^{-18}	3.7×10^{-16}	4.3×10^{-15}	2.0×10^{-14}	5.7×10^{-14}	1.3×10^{-13}
$1_{0,1}$	1.3×10^{-23}	7.3×10^{-18}	6.8×10^{-16}	7.1×10^{-15}	3.1×10^{-14}	8.3×10^{-14}	1.8×10^{-13}
$1_{1,1}$	1.0×10^{-22}	1.7×10^{-17}	1.1×10^{-15}	9.8×10^{-15}	3.9×10^{-14}	1.0×10^{-13}	2.1×10^{-13}
$1_{1,0}$	5.2×10^{-23}	1.5×10^{-17}	1.1×10^{-15}	1.1×10^{-14}	4.2×10^{-14}	1.1×10^{-13}	2.3×10^{-13}
$2_{0,2}$	1.2×10^{-21}	6.0×10^{-17}	2.6×10^{-15}	1.9×10^{-14}	6.7×10^{-14}	1.6×10^{-13}	3.1×10^{-13}
$2_{1,2}$	6.7×10^{-22}	5.3×10^{-17}	2.5×10^{-15}	1.9×10^{-14}	6.8×10^{-14}	1.6×10^{-13}	3.2×10^{-13}
$2_{1,1}$	5.6×10^{-21}	1.4×10^{-16}	4.7×10^{-15}	3.1×10^{-14}	1.0×10^{-13}	2.3×10^{-13}	4.3×10^{-13}
$2_{2,0}$	1.0×10^{-19}	5.9×10^{-16}	1.3×10^{-14}	6.5×10^{-14}	1.8×10^{-13}	3.8×10^{-13}	6.7×10^{-13}

[a]Rates in units of cm^3 sec^{-1}

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